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O-THREE: A HIGH ALTITUDE, REMOTELY PILOTED VEHICLE

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INTRODUCTION

A conceptual design for a remotely pilotely vehicle to be used for ozone research above 80,000 ft was developed as part of the one-semester NASA/USRA Aerospace Design course at Case Western Reserve University in Fall 1989.

The O-THREE design team chose as its mission requirements: a cruise altitude of 100,000 ft, a range of 1000 n.m., an endurance of 6 hr, a 1,000-lb payload, and a power to payload of 2 kW. These are based on the Boeing requirements for an ozone research vehicle. In addition, the vehicle should not be restricted to operation over any particular global location. Efforts were made to minimize atmospheric contamination that might increase the rate of ozone depletion and could cause discrepancies in data accuracy. Design was not limited to today's level of technology.

The design team was divided into four groups: Propulsion, Aerodynamics, Structures, and Stability and Control. Each group faced a unique design problem resulting from the unusual mission requirements. The Propulsion Group was concerned with the ability to operate at 100,000 ft where the density of air is 1/70th that of sea level. Because of the low dynamic pressure, the main Aerodynamic Group design goal was to find a high lift coefficient, low Reynolds number airfoil. The primary issue facing the Structures Group was to find strong, lightweight materials.

FINAL DESIGN

The final configuration can be found in Fig. 1. Specifications and weights are given in Tables 1 and 2, respectively. Performance estimates for cruise at altitude are listed in Table 3.

DISCUSSION

The Propulsion Group investigated possible propulsion devices and power sources to select a feasible propulsion system. Feasible was defined as a system capable of producing the required thrust at the working altitude. This was accomplished by a joint iterative process with the Aerodynamics Group.

From among the list of potential propulsion devices (turbofan, turboprop, turbojet, internal combustion engine, rocket, balloon, Stirling engine, electric motor) the electric motor was chosen for its high efficiency, low specific weight, and minimum environmental impact. The final airplane configuration necessitated the use of two motors, one per fuselage. Samarium-cobalt electric motors were selected. These motors use rare-earth permanent magnets to achieve efficiencies of 90-95% and lightweight composite materials for an expected specific weight of 0.57 lb/hp. Their brushless design eliminates the arcing problems associated with conventional motors operating in such a low-density atmosphere.

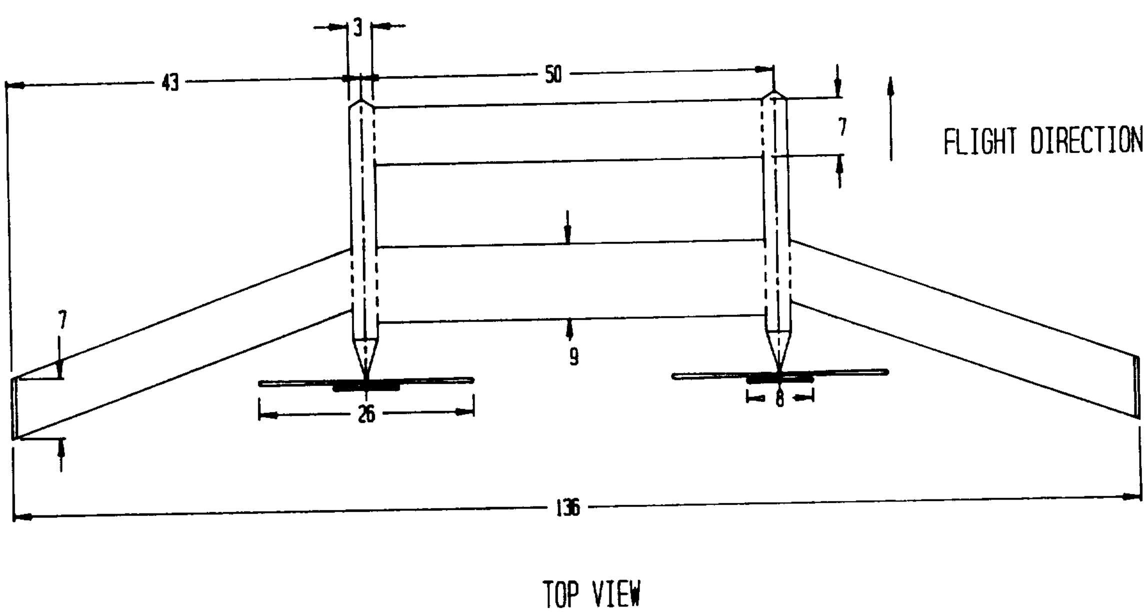


Fig. 1. Vehicle Configuration

Table 1. O-THREE Specifications

Airfoil	LNV109A
Power plant	Solid oxide fuel cells
Engines	Samarium cobalt electric motors
Weight at takeoff	8198 lb
Weight at cruise	7853 lb
Weight empty	5558 lb
Wing span	136 ft
Wing area	1402 ft^2
Aspect ratio	17.6 ft
Distance between fuselages	50 ft
Fuselage diameter	3 ft
Fuselage length	30 ft
Small propeller diameter	8 ft
Large propeller diameter	26 ft
Canard	
Span	50 ft
Chord	7 ft
Area	350 ft^2
Max thickness	0.9 ft
Midsection wing	
Span	50 ft
Chord	9 ft
Area	450 ft^2
Max thickness	1.2 ft
Swept wing	
Span	43 ft
Chord	7 ft
Area	283 ft^2
Sweep angle	20°
Taper ratio	1.0

Table 2. O-THREE Weight Distribution, Cruise Conditions

	(lb)
Propulsion	
Fuel	
Oxygen (gaseous)	2040
Hydrogen (gaseous)	256
Electric motors (2)	400*
Fuel cells (12)	1000*
Electric converters (2)	100*
Large propellers (2)	200*
Small propellers (2)	100*
Structures	
Midsection wing	523
Swept wing (2)	909
Canard	438
Vertical stab/winglet (2)	100
Fuselage (2)	607
Other	
Landing gear (4)	120*
Payload	1000
Controls	60*
Total	7853

*Allocated weight

Table 3. Performance Characteristics

Takeoff velocity	44 mph
Endurance at cruise (100,000 ft)	6 hrs
Cruise velocity	0.55 Mach
Power required (cruise)	250 kW
Lift-to-drag ratio (cruise)	25
Range	1930 n.m.
Glide angle	2.3°

The possible power sources were constrained by the choice of propulsion device to those that produced electric power. From the list of potential power sources (solar, hydrocarbon fuels, laser-plasma, microwave, nuclear, battery, fuel cells) fuel cells were chosen, since cutting edge fuel cell technology provided the highest specific power, the best competitive overall efficiency, and the most compact package of any power source investigated.

The AIResearch Division of the Garrett Corporation (Torrance, CA) has developed a monolithic solid-oxide fuel cell design that utilizes a ceramic honeycomb structure to provide a compact package. Garrett's goal for the 1990s is a 9-in × 9-in cross-section producing an output of 67 hp. The fuel cell's specific power is about 0.37 hp/lb. This is 4.5 times greater than the specific power for a diesel generator and 7.5 times greater than that of a conventional fuel cell. Fuel cells tested have demonstrated a 60-70% efficiency. The only product generated by the reaction is water. This solves the concern over polluting the atmosphere. Argonne National Laboratories has operated cells for up to 700 hr without any noticeable degradation. Finally, the fuel cells are modular so that units can be stacked to increase power output, while the monolithic design provides a strong structure and the ability to automatically seal at the edges.

The final propulsion system configuration would consist of the following:

1. Monolithic solid-oxide fuel cells utilizing hydrogen and oxygen as fuel and oxidizer, respectively;
2. Power conversion units to transform the fuel cell electrical output to an acceptable motor electrical input;
3. Two samarium-cobalt permanent magnet electric motors;
4. Reduction gear box to match each motor with the necessary propeller speeds;
5. Two pairs of pusher propellers, one size for takeoff and the other for cruise.

Aerodynamics

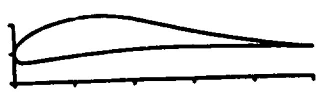
Subsonic flight at 100,000 ft posed several unique aerodynamic problems.

Airfoil selection. Low dynamic pressure is the consequence of cruising at 100,000 ft near the minimum power required condition. Based on preliminary estimates, chord Reynolds numbers were expected to range between 200,000 and 600,000. Therefore, a broad search of the technical literature on low Reynolds number airfoils was conducted. The criteria used for selecting an airfoil were: (1) high lift coefficient, $C_L > 1$; (2) predictable performance at Reynolds numbers between 200,000 and 600,000; and (3) minimum thickness-to-chord ratio. A high lift coefficient was sought to reduce the wing area and flight speed. The second criterion was established to eliminate any airfoil displaying lift hysteresis at the cruise Reynolds numbers. In general, lift hysteresis was a concern only at Reynolds numbers below 375,000. Minimum thickness-to-chord ratio was desired to reduce weight. The Liebeck airfoil, LNV109A, was one that met all three conditions. Maximum performance for this airfoil occurred for Reynolds numbers greater than 400,000. The characteristics of the LNV109A can be found in Fig. 2. The operating lift coefficient was chosen to be 1.2 at an angle of attack of 8°.

AIRFOIL CHARACTERISTICS

Airfoil: LNV109A
Designers: R.H. Liebeck and P. P. Comacho
Douglas Aircraft Company

(t/c) max = 13%
Location of (t/c) max = 0.25c
Design Re = 400,000
$0.5 < C_L < 1.5$
C_L stall = 1.8
α stall = 14°
Cm = −0.05



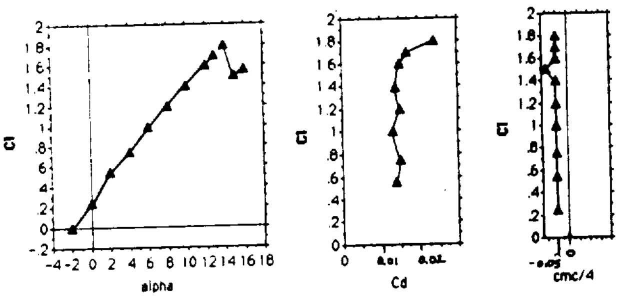


Fig. 2. Airfoil Characteristics

Configuration. The twin fuselage configuration was chosen primarily for structural reasons. In order to lift approximately 8000 lb with an operating lift coefficient of 1.2, 1402 ft^2 of wing area was needed. This wing area is divided into four sections: a canard, a main wing midsection, and two swept wings. Because performance degradation occurs for Reynolds numbers below 375,000, chordlengths were chosen to maintain chord Reynolds numbers of 400,000 or greater. The Mach number at cruise is 0.55.

The outboard wings were swept 20° in order to keep the wingtips as far aft of the center of gravity as possible since the vertical stabilizers would be mounted there. Pusher-props were used to eliminate the detrimental effects of propwash over the main lifting surfaces.

Drag power required estimation. The BASIC Aircraft Performance Analysis program developed by Kern International was used to predict the drag of the entire airplane. Modifications were made to the program's atmosphere subroutines using the equations given by the 1976 U.S. Standard Atmosphere. Also, because the Kern program could accept only conventional designs, O-THREE was modeled as a sailplane with a wingspan of 136 ft and a total wing area of 1402 ft^2. From this, a new aspect ratio and chord length were calculated. Secondly, a single fuselage equivalent of the twin fuselage arrangement was obtained by keeping the wetted area and the front area constant.

The parasite drag coefficient at cruise is 0.0156. This is probably a conservative estimate of the drag coefficients because the skin friction coefficient was evaluated for turbulent flow. The effects of sweeping the two outboard wings were also not taken into consideration and would act to reduce drag.

The power required for level, unaccelerated flight at 100,000 ft at M = 0.55 is about 250 kW. This is close to the minimum power required condition.

Structures

The structural analysis of O-THREE was conducted for cruise conditions at 100,000 ft. The structural design process began when the geometry of the plane (Fig. 1) and an estimation of the weight (8000 lb) were determined.

Using the initial weight estimate of 8000 lb and a wing area of 1402 ft^2, a wing loading of 5.71 lb/ft^2 was calculated. The wing weight was estimated at 1.3 lb/ft^2 from a Lockheed technical report that used lightweight composites. The structural forces and moments were obtained by integrating over strips in a spanwise direction. The net force was the difference between the lifting force and the weight. The initial assumption was that every part of the wing produced ideal lift.

The main spar of the swept wings was modeled as a cantilever beam. The midsection wing and canard were beams fixed at both ends by the fuselage. A wing loading of three times that of cruise or 17.12 lb/ft^2 was used in the calculations.

Two types of spar geometries were examined, a shear web and a circular tube. The circular tube was chosen for its potential to store fuel in the center. The midsection spar contains enough empty volume to carry 45.6 ft^3 of gaseous hydrogen at 1 atm, and the canard spar can hold 22.8 ft^3 of gaseous oxygen. This is the fuel needed for a 6-hr endurance.

The material chosen for the spar was a graphite (50%) epoxy composite. The estimated yield strength was 110,000 lb which was used for σ_{allow}. This material was chosen for its strength-to-weight ratio, its superior fatigue properties, and corrosion resistance as compared with typical aircraft materials. The spars can be manufactured using an autoclave.

The maximum deflection of these spars under a wing loading of 17.12 lb/ft^2 was calculated using the same beam models. The maximum deflection for the tips of the swept wing was 70.6 in. This includes a point force of 50 lb hanging on the tip due to the vertical stabilizer/winglet. The maximum deflection of the midsection wing and the canard is 8.2 in and 8.9 in, respectively. This maximum occurs at the center of the wing. Time has not permitted the iteration of these calculations for cases when the spars are fueled up.

The ribs are formed of rigid polyurethane (Pur) foam, 3/4-in thick, and wrapped in 1/32-in Kevlar 49 (K49). The ribs form the shape of the LNV109A airfoil. The compressive strength of the foam combined with the tensile strength of the K49 make a strong sandwiched composite.

The ribs were held to the spars in two different ways. On the midsection wing, spar caps were placed on each side of the rib and adhere to the rib and spar. On the swept wings and canard the spar spacers were adhered between the spar and the ribs.

Table 4. Structural Specifications

Item	Material	Weight	Dimensions
1. Midsection Wing			
a. Spar	GR/EP	167 lb	Ro = 6.625, Ri = 6.5 in L = 50 ft
b. Ribs (25)	Pur/K49	84 lb	T = .75 in W = .5 in
c. Skin	GR/EP	219 lb	T = 1/32 in
d. Trailing edge	Pur/EP	51 lb	L = 50 ft, W = 6.4 in T = airfoil shape
e. Spar caps (50)	GR/EP	3 lb	L = 4 in, W = .5 in
2. Canard			
a. Spar	GR/EP	119 lb	Ro = 4.725, Ri = 4.6 in L = 50ft
b. Ribs (25)	Pur/K49	65 lb	(Same as 1.b)
c. Skin	GR/EP	170 lb	(Same as 1.c)
d. Trailing edge	Pur/K49	82 lb	L = 50 ft, W = 2.25 in T = airfoil shape
e. Spacers (25)	GR/EP	2 lb	(Same as 1.e)
3. Swept wings (2)			
a. Spars	GR/EP	408 lb	Ro = 4.5, Ri = 4.25 in L = 45.7 ft
b. Ribs (50)	Pur/K49	130 lb	(Same as 1.b)
c. Skin	GR/EP	293 lb	(Same as 1.c)
d. Trailing edges	Pur/K49	75 lb	L = 45.7 ft, W = 2.25 in T = airfoil shape
e. Spacers (50)	GR/EP	3 lb	(Same as 1.e)
4. Fuselage (2)			
a. Bulkheads (20)	GR/EP	231 lb	W = 1, T = 1.5 in
b. Stringers (16)	Pur/K49	239 lb	W = 2, T = .75 in L = 30 ft
c. Skin	GR/EP	137 lb	(Same as 1.c)
Total	2478 lb		

The trailing edges of all the wings were also constructed using a Pur core wrapped in K49. This piece was fastened onto the end of the ribs with adhesive. The skin for all the wings and the fuselage are graphite epoxy face sheets of 1/32 in. The fuselage consisted of graphite epoxy bulkheads with polyurethane Kevlar sandwiched stringers.

All the structural data can be found in Table 4. No consideration was made for twist about the spar due to the pressure distribution over the wing. The next iteration in this ongoing design process will be to replace the estimated wing weight per area (1.3 lb/ft^2) with the results of this first analysis. The exact configuration of the control surfaces and landing gear also needs to be completed.

Stability and Control

Static longitudinal stability. O-THREE utilizes a long-coupled canard in that the forward plane is placed at an appreciable distance in front of the main wing. Since O-THREE is an unconventional design, several simplifying approximations were made. The main wing was modeled as a rectangular wing even though the two outboard wings were swept 20°. Dimensions of the rectangular main wing model are: chordlength of 7.7 ft and a wingspan of 136 ft. The maximum lift coefficients, assumed at both takeoff and cruise, of all lifting surfaces was 1.2. The aerodynamic center was calculated to be 6.34 ft behind the leading edge of the main wing midsection. The center of gravity was computed to travel from 4.55 ft in front of the main wing leading edge at the beginning of cruise, to 0.51 ft in front of the main wing leading edge when the fuel is depleted. The neutral point moves correspondingly from 2.33 ft behind the main wing leading edge to 0.9 ft behind the main wing leading edge. O-THREE did meet the criteria for static longitudinal stability with static margins for takeoff and cruise calculated to be 86% and 16%, respectively. Static directional and dynamic stability analyses were not completed because of time constraints.

It is suggested that pitch control be achieved by flaps attached to the main wing midsection. Roll would be controlled by spoilers located on the outboard swept wings, and yaw control by two rudders attached to the vertical stabilizers on the wingtips. Additional yaw control could be achieved by varying the propeller speeds.